



Summary of the Large Civil Tiltrotor (LCTR2) Engine Gearbox Study

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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Abstract

In support of the Fundamental Aeronautics Program, Subsonic Rotary Wing Project, NASA is continuing to study the Large Civil Tiltrotor (LCTR) concept to help define/refine vehicle, system and subsystem attributes. These attributes can then be used to define performance requirements and identify new or advanced technologies to achieve an operational vehicle class. As part of this goal, NASA contracted with The Boeing Company and its subcontractor Rolls-Royce to perform an investigation of different combinations of engine and gearbox variability to achieve a maximum of 50 percent rotor tip speed reduction from hover to cruise conditions. Previous NASA studies identified the 50 percent rotor speed reduction minimized vehicle gross weight and fuel burn. The LCTR2 (LCTR—iteration 2) was the contracted study baseline for initial sizing. Rotor tip speed ratios (cruise to hover) of 100, 77, and 54 percent were analyzed for each combination of engine and gearbox speed reduction to achieve the chosen rotor tip speed ratio. Three different engine and gearbox technology levels were assumed; commercial off-the-shelf (COTS), entry-in-service (EIS) in 2025 and EIS in 2035. These technology levels were applied to determine each particular effect on vehicle gross weight and fuel burn, while other vehicle technologies were assumed constant. This report summarizes the work performed that is being put together into a comprehensive NASA contractor report. Some background on the LCTR concept and baseline vehicle will be given and then a discussion concerning the technical approach utilized. Major study assumptions and results will be presented and discussed. Finally conclusions will be drawn as well as suggestions provided for future efforts.

Introduction

The NASA Heavy Lift Rotorcraft System Investigation (Ref. 1) identified a large tiltrotor as the best concept to meet commercial airspace requirements for the future, short-haul regional market. Through further analysis and refinement, the notional tiltrotor evolved into a conceptual vehicle designated as LCTR2 (Large Civil Tiltrotor—iteration 2) (Ref. 2) as seen in Figure 1.

This vehicle was designed to carry 90 passengers at 300 knots with at least a 1,000 nautical mile (nm) range; powered by four turboshaft engines rated at 7,500 shaft horsepower (SHP) each (at Sea level Static (SLS) conditions). Other design features included a rotor tip speed of 650 feet per second (fps) in hover and 350 fps during cruise, enabled by a two-speed gearbox. This range of rotor tip speeds was needed to achieve the high level of performance and efficiency at two very different flight conditions for the reference design mission shown in Figure 2. Additional vehicle and mission details can be found in Reference 2.



Figure 1.—Conceptual view of LCTR2.

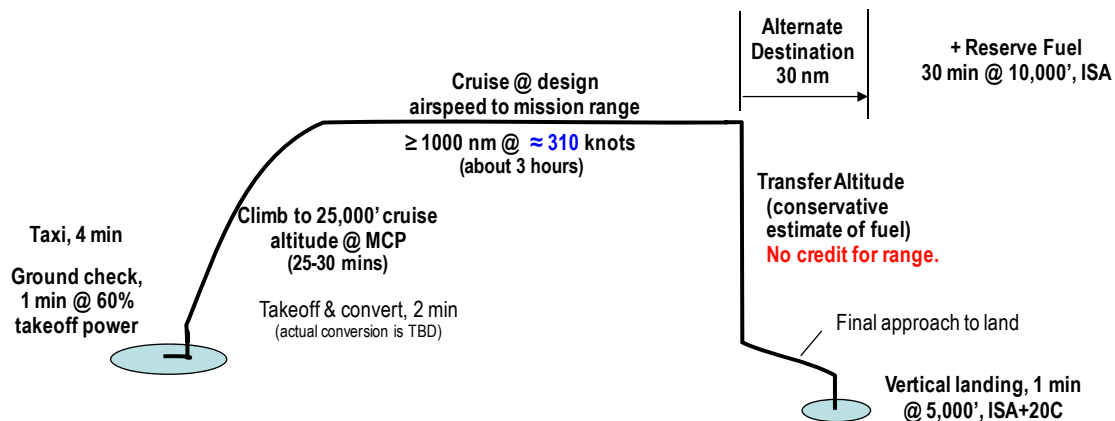


Figure 2.—LCTR2 design reference mission.

The LCTR2 currently serves as a representative vehicle and mission for the Fundamental Aeronautics Program (FAP) Subsonic Rotary Wing (SRW) project to further define performance levels required for these vehicle concepts to be practical. Gaps between these study performance levels and the state-of-the-art would be used to identify research opportunities. Further studies were envisioned to delve into additional detail to identify specific research areas. A study (Ref. 3) was conducted to evaluate the net benefits of advanced technologies for two conceptual civil transport rotorcraft (single-main rotor compounds and civil tiltrotor), with different mission cruise speeds and payloads from the LCTR2. Engine technology was identified as giving more benefits to direct operating cost per available seat-mile than other technology groups included. This further motivated NASA to study engine and gearbox combinations and technologies to help guide engine and drive system research to maximize the gain from its technology investment. The subject of this report is to summarize the NASA-contracted effort (NNA06BC41C, Task Order 10) performed by The Boeing Company and Rolls-Royce Corporation to identify and evaluate engine and drive system concepts that could achieve the almost 50 percent rotor tip speed reduction identified in the previous NASA studies. A NASA contractor report (CR) is in process to give comprehensive details concerning the background, study methodologies and substantiation, results, and conclusions for that effort.

Study Overview

Per the original statement of work for the contract: “The main emphasis of this effort is to identify the engine and gearbox/transmission technology barriers/challenges/needs for achieving the 50 percent rotor tip speed variation with a fixed rotor diameter, vehicle, and mission.” The contracted effort was divided into 6 tasks (5 engineering tasks and one for reporting and administration):

- Task 1 is an evaluation of LCTR2 vehicle sizing and performance characteristics assuming COTS engine and drive system technologies. This task includes development of sizing methodology, baseline vehicle and system characteristics as well as initial sizing for 54 percent rotor cruise tip speeds.
- Task 2 is executed by Rolls-Royce team members to generate engine information for advanced technology engines (EIS 2025 and 2035) that will be used in the performance analysis tasks that follow.
- Task 3 generates information for the drive system configurations and performance (EIS 2025 and 2035).
- Task 4 is comprised of analysis tasks conducted by Boeing and Rolls-Royce to evaluate benefits for advanced technologies and operational scenarios conducted with 54 percent rotor cruise tip speeds. The primary criteria used to evaluate performance will be system weight and overall fuel burn.
- Task 5 identifies technology challenges and needs for various parts of the overall system that will be addressed through subsequent research and development efforts.
- Task 6 is for reporting and administration related efforts.

To complement the NASA-derived cruise to hover rotor tip speed ratio of 54 percent, two additional cruise rotor tip speed ratios were included to get preliminary indications of system effects (changes in fuel, component and vehicle weights and performance, especially noting those changes in the engine and drive systems) that might offset the improvements in rotor efficiency achieved through the rotor cruise tip speed reduction. Finally, the rotor cruise tip speed reduction could be achieved through a multispeed gearbox alone, a gas turbine engine with a large operating speed range power turbine alone (requiring only a single-speed gearbox), or a combination of engine and multispeed gearbox technologies. The combination of parameters used in this study is shown in Table 1.

TABLE 1.—ENGINE-GEARBOX STUDY MATRIX

Rotor design cruise tip speed, percent	Engine cruise/Normal rpm, percent	Drive system cruise/Hover rpm, percent
650 fps (100%) Reference	100	100%
500 fps (77%) Mid-value	100	77% (2-speed)
	77	100%
350 fps (54%) NASA goal	100	54% (2-speed)
	77	70% (2-speed)
	54	100%

Analysis Methodology and Component Results

Analysis tools for vehicle sizing and performance evaluation were devised from existing spreadsheet-based tools. These tools included many of the performance and sizing procedures from VASCOMP (Refs. 4 and 5) and were designed to facilitate “concept evaluation” over the matrix of engine-gearbox combinations mentioned previously for the three engine and drive system technology levels evaluated (COTS, EIS 2025, and EIS 2035). Some of the major assumptions/methodology used for the study are given below:

- Resize vehicle with each engine/transmission/rotor tip speed to meet mission range and payload requirements.
- Fix vehicle system technology levels at 2025 technology, to isolate effect of engine/drive system technology changes.
- Maintain engine and drive systems at similar technology levels (COTS, 2025 or 2035).
- Scale engine size to meet most stringent requirement of hover, one-engine inoperative (OEI), or cruise power levels (generally hover requirements set engine power).
- Size drive system for maximum torque condition for either hover or cruise, recognizing that this could limit torque at other flight conditions.
- Assume rotor speed reduction occurs right after transition from hover to climb/cruise phase. This assumption resulted in torque-limited climb power for 500 and 350 fps cases. This torque-limit could have been alleviated if the study assumed rotor speed reductions occurred later in flight. Review of results determined that this limit would only have minimal effects on the overall vehicle fuel burn or mission time (since the 1000 nm mission is cruise-dominated).

Engine Performance

The NASA, Boeing and Rolls-Royce team defined the engine technology strategy that would be used by Rolls-Royce to develop engine models and provide scalable engine data consistent with technology for COTS, EIS 2025, and EIS 2035. The COTS engine was based on a conventional (single-spool), all-axial turbofan core modified to a turboshaft engine (the power turbine would be on its own shaft), with an overall pressure ratio equivalent to current engines. A representative image of the COTS engine is given in Figure 3. Engine performance is shown in Figure 4 assuming a conventional power turbine, optimized for a limited operating speed range around 95 percent (typical for conventional aircraft mission and duty cycle). It shows some power and efficiency losses for power turbine operation at 77 percent speed (which were the most significant at high power levels). At 54 percent speed, there were significant losses in maximum power available as well as fuel efficiency, the subsequent effects on vehicle sizing will be shown later.

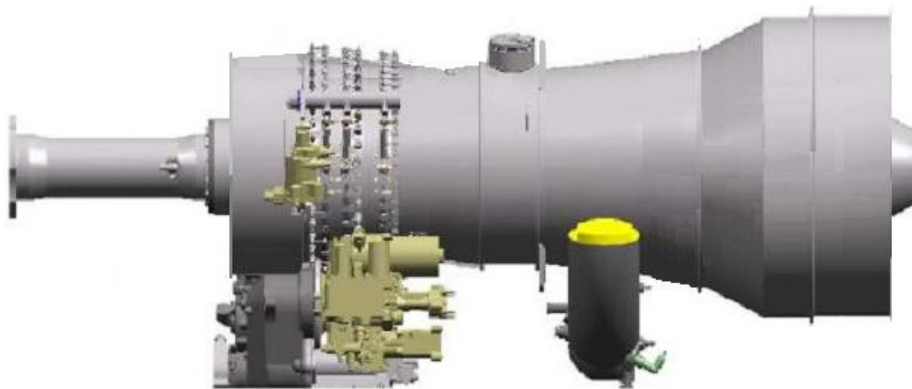


Figure 3.—Representative image of the COTS engine.

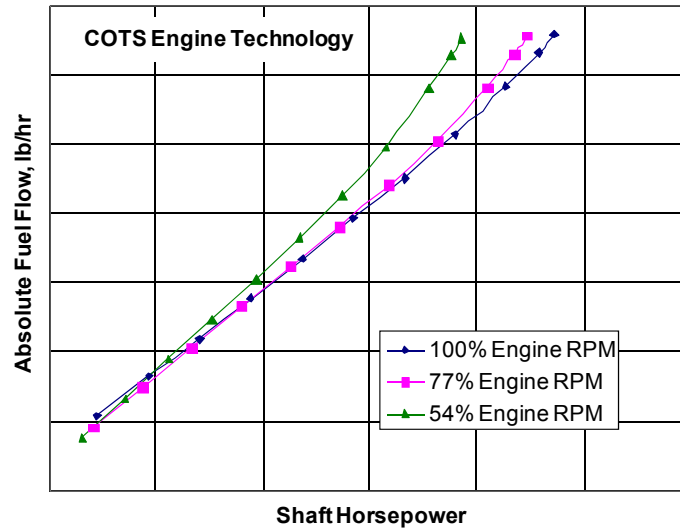


Figure 4.—COTS engine performance.

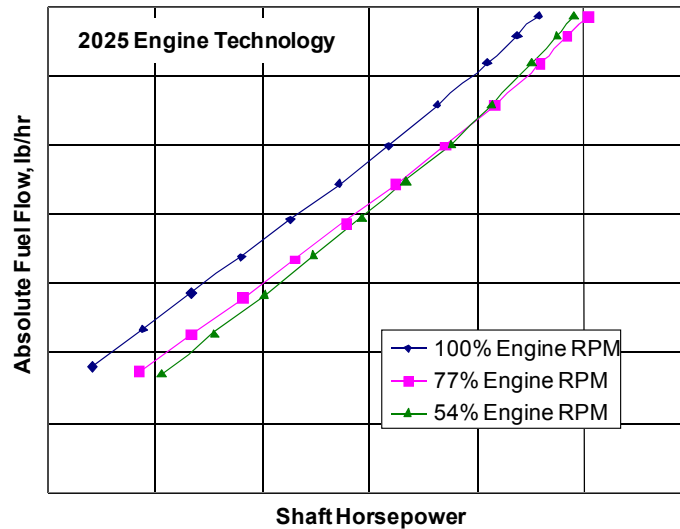


Figure 5.—2025 engine performance with wide speed range power turbine optimized for 77 percent rpm.

For the EIS 2025 technology engine, it was assumed that a significantly improved, new engine core would not be available. Enhancements to the core engine would be limited to material and cooling updates applied to the COTS engine and the core would be similar to the COTS engine already shown. With a standard power turbine, performance would be similar to the COTS engine, although there would be additional margins available that could be used to improve maintainability or some additional power capability. The EIS 2025 timeframe would be sufficient for incorporation of a wide-speed range power turbine (employing variable geometry), which could be used to improve performance at reduced power turbine speeds. Since the LCTR2 mission is cruise dominated, power turbine design was optimized around the 77 percent speed point (which would improve cruise performance at reduced engine speed). Engine performance for the EIS 2025 engine with a wide speed range power turbine is shown in Figure 5. The wide-speed range turbine gave excellent performance at its design speed and almost as good at 54 percent rpm. Even with variable geometry, performance fell off for the 100 percent rpm condition. The advances in materials and cooling assumed available for the core would give some increased capability in turbine inlet temperature, which was used to maintain power for the hover condition, to prevent oversizing the 2025 engine and further penalizing the vehicle.

For the EIS 2035 engine, it was assumed that a new, advanced core would be available. For this advanced core, it was further assumed that compression would be accomplished in two spools, increasing maximum temperatures and pressures present in the cycle (versus the COTS and 2025 engines), and significantly improving engine efficiency and weight. To maintain compressor performance at low exit corrected flows, the high pressure compressor was assumed to be an axi-centrifugal design. It also included a wide-speed range power turbine (three-spool engine overall), to maximize fuel efficiency at an engine speed of 77 percent. A representative image of this engine is shown in Figure 6. Engine performance for the EIS 2035 engine with a wide speed range power turbine is shown in Figure 7. The advanced core combined with the wide speed range power turbine was able to achieve high power and efficiency over the entire rpm operating range, minimizing those losses for operation at 100 percent rpm exhibited in the EIS 2025 engine results.

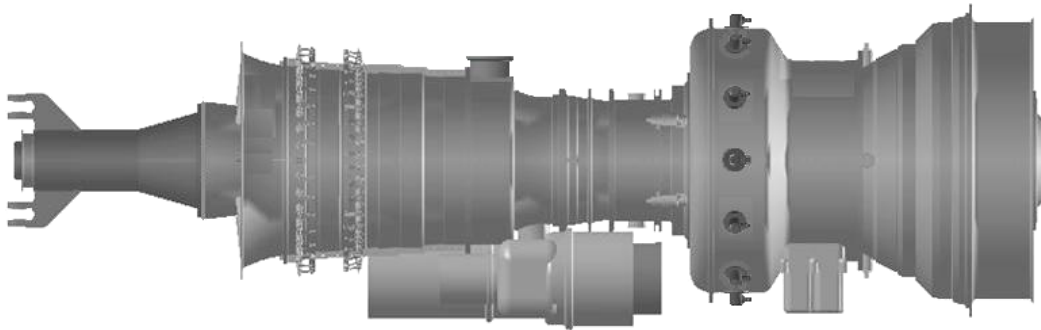


Figure 6.—Representative image of the EIS 2035 engine.

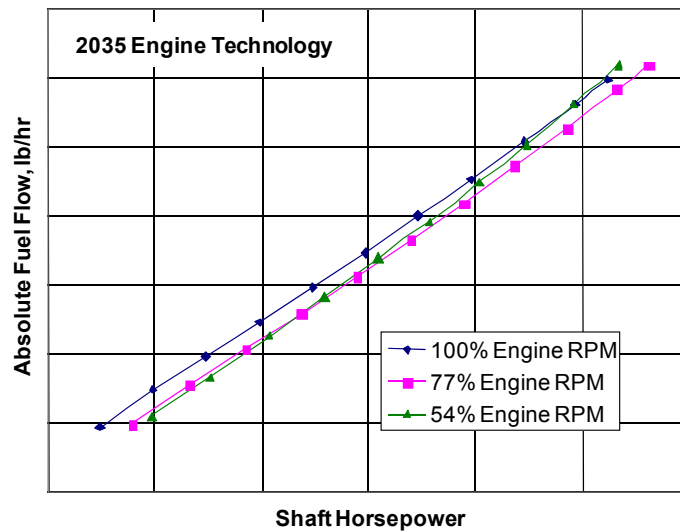


Figure 7.—2035 engine performance with wide speed range power turbine optimized for 77 percent rpm.

Engine Weight

The engines were scaled to meet maximum power required over the mission (which generally was for the hover condition). The addition of the wide-speed range power turbine incurred a significant weight increase for the 2025 and 2035 engines; preliminary estimates put the additional dry weight at 200 and 150 lb, respectively, per unscaled engine. Engine weights at the unscaled power level are shown in Table 2.

Drive System

The NASA LCTR2 vehicle configuration parameters and mission specifics were used to develop configuration data and concepts for the integrated engine and drive systems used in the study. As a Tiltrotor vehicle, the LCTR2 general arrangement is similar to the V22 Osprey drive system. The LCTR2 configuration has evolved to a high wing, tilting nacelle aircraft like the V22 in many respects except with 4 engines, 2 engines at each nacelle. The nominal drive system architecture (using helical gears for idlers and bull gear) was devised after consideration of many alternatives and a block diagram is shown in Figure 8. This diagram represents a (single speed ratio) direct drive configuration (rotor speed variations are achieved through engine speed variation).

Speed reduction capability for the drive systems were based on compound planetary systems. The speed is changed by restraining an element of the planetary system, either a ring gear or carrier with a (multiple disk) clutch, causing the gear ratios to change. Figure 9 shows a schematic arrangement “Configuration B” that proved favorable for weight and operating characteristics to the extent examined in this study. The speed change modules are incorporated into the drive system as shown in the block diagram of Figure 10.

TABLE 2.—UNSCALED ENGINE WEIGHTS

Engine	Installed SHP (Maximum rated power at sea level, static)	Engine dry weight, lb
COTS	8100	1,356
2025	8088	1,556 (1,356+200)
2035	8088	1,020 (870+150)

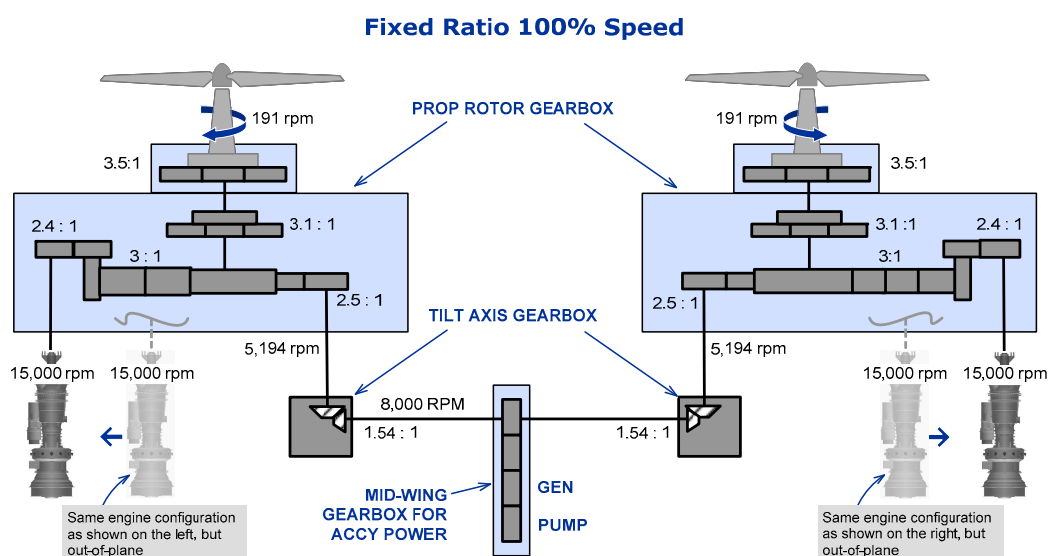


Figure 8.—Drive system block diagram for the reference LCTR2 vehicle configuration.

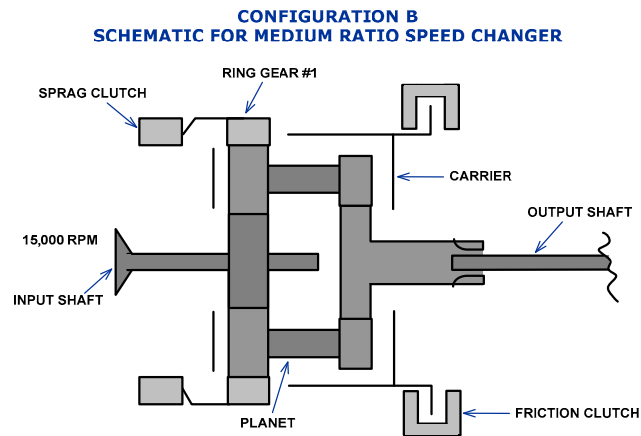


Figure 9.—Speed changing compound planetary schematic.

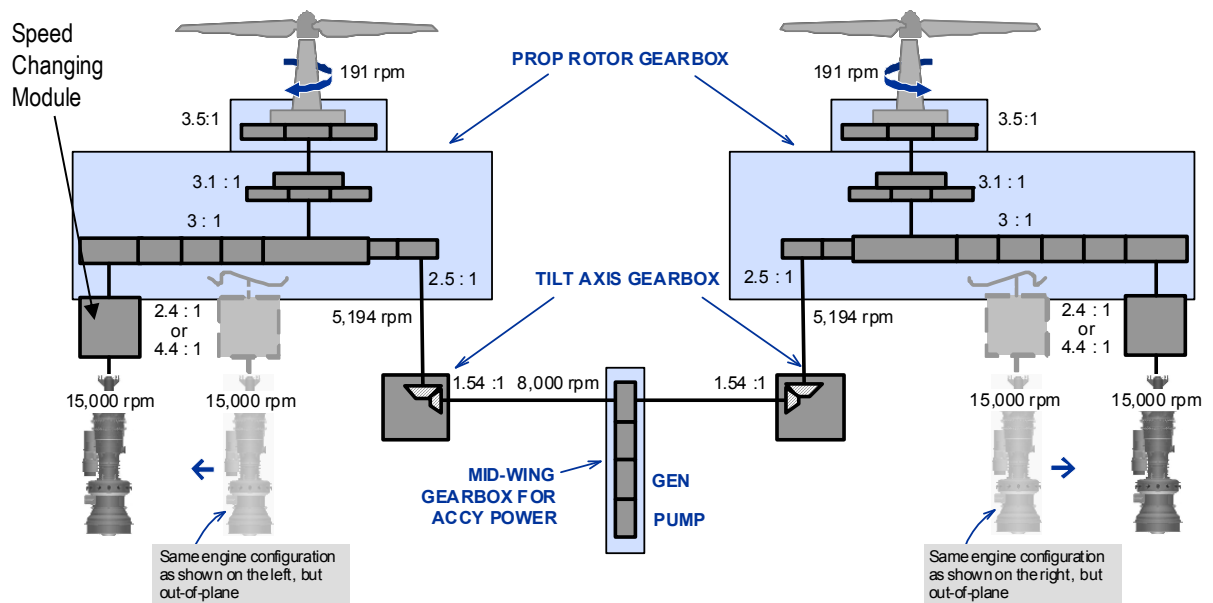


Figure 10.—Drive system block diagram with speed changing modules.

From these configurations, estimates were made for weights and power losses for all combinations of engines and gearbox speed changes to meet the desired rotor cruise tip speeds. To ease comparisons, weight data is given assuming 7,500 hp at the lowest operating speed. This weight information is subsequently scaled to the appropriate power within the vehicle sizing program. Weight trends for current production and applying a weight technology factor of 0.8 (20 percent weight reduction) for COTS technology is given in Table 3, along with the xcruise speed percentage power loss. For the EIS 2025 technology, it was assumed the weight technology factor would be 0.75 (25 percent weight reduction from current production) and a 5 percent reduction in cruise power losses from COTS levels. For the EIS 2035, the weight technology factor was estimated to be 0.70 (30 percent weight reduction from current production) and cruise power losses would be 10 percent less than COTS levels. The resulting weights and percentage cruise power losses are given in Table 4. It can be seen that reducing rotor speeds increases the drive system weight, due to the increase in maximum torque or mission time at high torque levels. For multispeed gearboxes, increasing the amount of speed reduction achieved through the gearbox also increases the drive system weight.

TABLE 3.—COTS DRIVE SYSTEM WEIGHTS AND CRUISE POWER LOSSES

Configuration	Speed, percent	Engine, percent	Drive, percent	Rotor, rpm	Tip speed, fps	Trend weight, pounds, Current production	COTS weight, pounds, Technology factor 0.8	COTS power loss at cruise speed, percent
1	100	100	100	191.0	650.0	11,236	8989	4.10
2B	100	100	100	191.0	650.0	11,758	9406	4.70
2B	77	100	77	147.1	500.5	11,758	9406	4.35
1	77	77	100	147.1	500.5	11,236	8989	3.85
2B	77	77	100	147.1	500.5	11,872	9497	4.35
3B	54	100	54	103.1	351.0	12,086	9669	3.90
1	54	54	100	103.1	351.0	11,236	8989	3.40
2B	53.9	77	70	102.9	350.4	11,872	9497	3.80

TABLE 4.—2025 AND 2035 DRIVE SYSTEM WEIGHTS AND CRUISE POWER LOSSES

Configuration	Speed, percent	Engine, percent	Drive, percent	Rotor, rpm	2025 weight, pounds, Technology factor 0.75	2035 weight, pounds, Technology factor 0.70	2025 power loss, percent Technology factor 0.95	2035 power loss, percent Technology factor 0.90
1	100	100	100	191.0	8427	7866	3.90	3.69
2B	100	100	100	191.0	8819	8231	4.47	4.23
2B	77	100	77	147.1	8819	8231	4.13	3.92
1	77	77	100	147.1	8427	7866	3.66	3.47
2B	77	77	100	147.1	8904	8310	4.13	3.92
3B	54	100	54	103.1	9065	8460	3.71	3.51
1	54	54	100	103.1	8427	7866	3.23	3.06
2B	53.9	77	70	102.9	8904	8310	3.61	3.42

Rotor Performance

Although NASA has performed extensive studies to refine the LCTR2 rotor system design, Boeing applied NASA descriptions of the LCTR rotor to perform an independent, in-house estimate of rotor hover and cruise performance. The NASA geometric twist distribution was maintained for the 350 fps cruise tip speed, but was modified for the two additional cruise tip speeds (500 and 650 fps) with the goal of locally aligning the blade with oncoming flow at 300 knots for vehicle cruise. Resource constraints permitted no blade optimization to further refine the resulting blade twist distributions for cruise or to balance the design for hover performance. A comparison of rotor blade twist distributions is shown in Figure 11 and compared to the helical inflow angles for each rotor, operating at 310 knots. Boeing applied a bi-linear twist distribution for the 500 fps tip speed, similar to the NASA twist parameterization. A bi-linear twist distribution proved to be inadequate to properly align the blade for the 650 fps cruise tip speed and a tri-linear twist was used instead. Maps of rotor cruise efficiency from the Boeing B08 (Refs. 6 and 7) analysis are presented Figures 12 to 14.

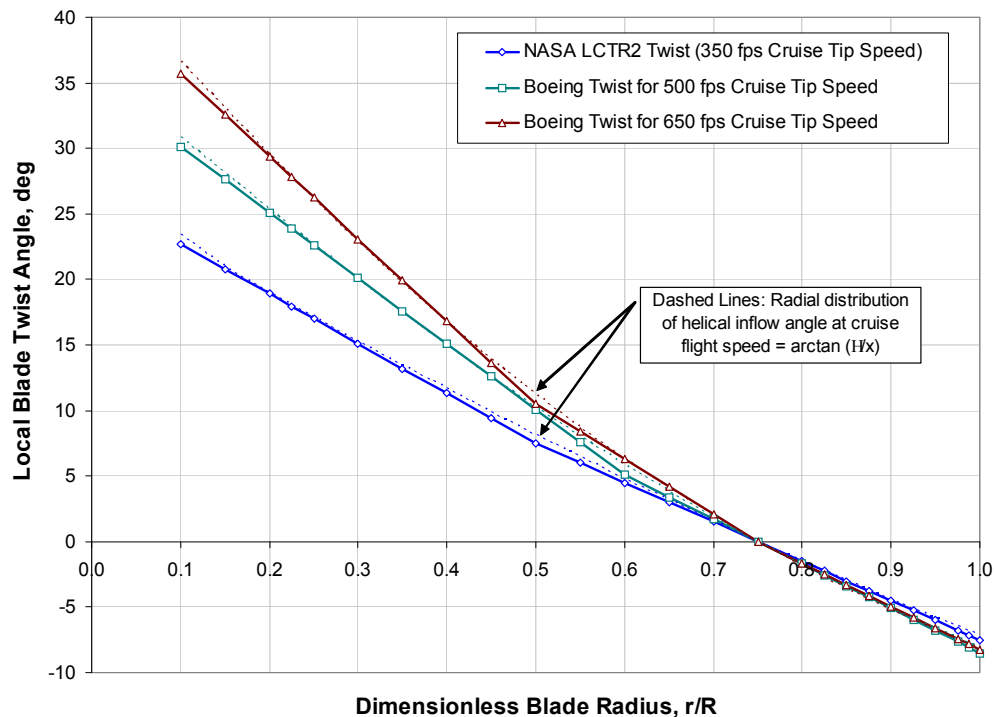


Figure 11.—Comparison of rotor blade twist distributions.

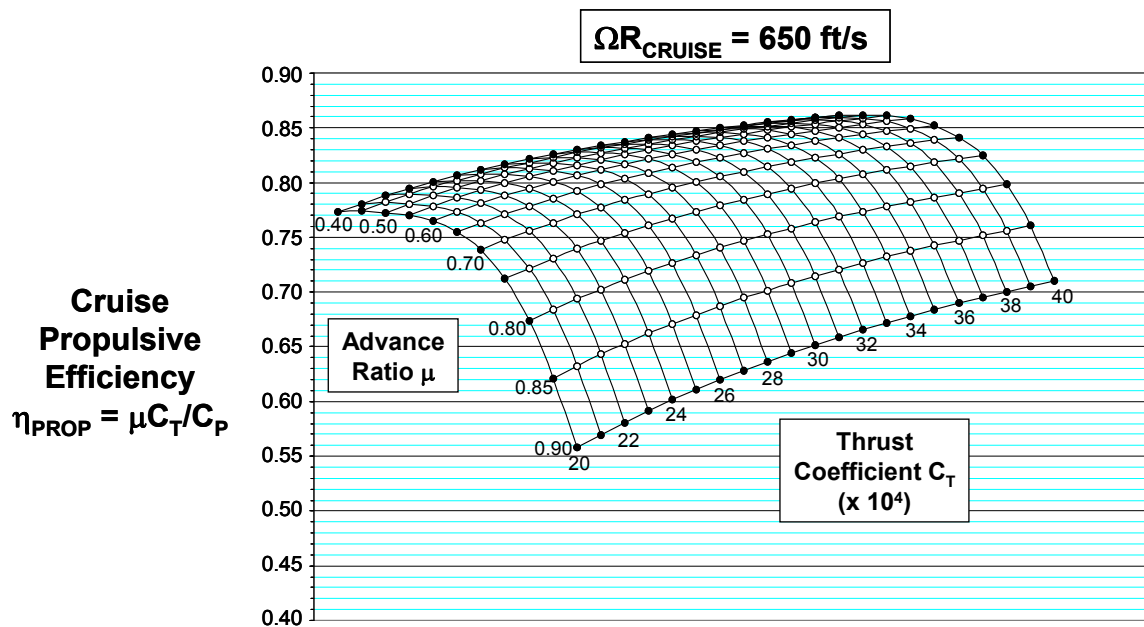


Figure 12.—Rotor cruise propulsive efficiency, 650 fps cruise tip speed design.

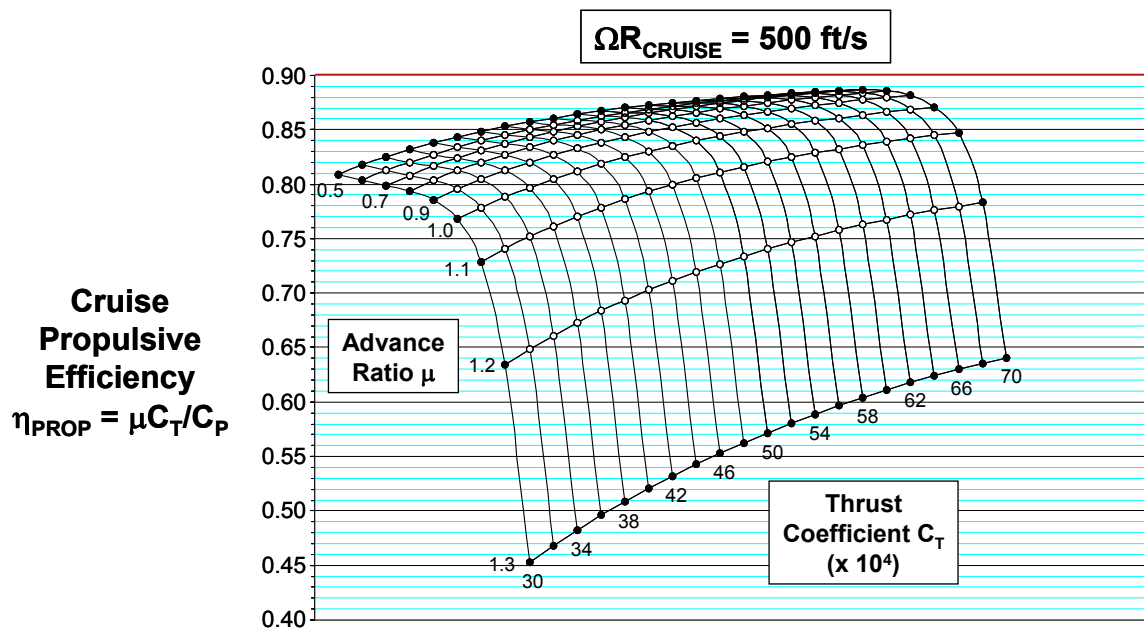


Figure 13.—Rotor cruise propulsive efficiency, 500 fps cruise tip speed design.

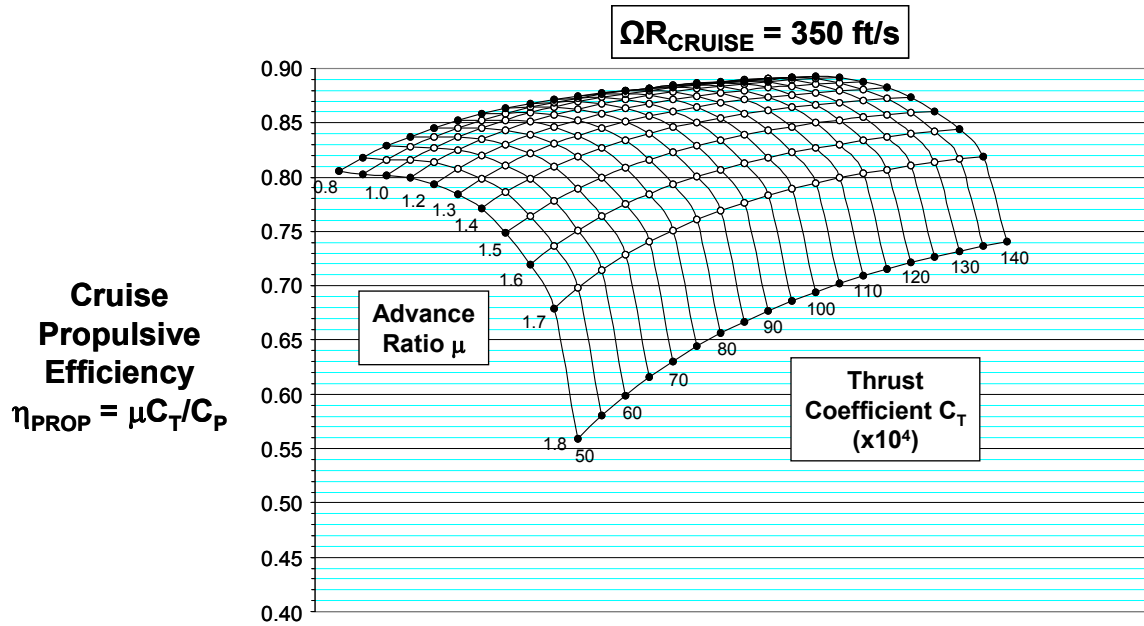


Figure 14.—Rotor cruise propulsive efficiency, 350 fps cruise tip speed design.

Results and Discussion

The NASA LCTR2 vehicle and mission was then modeled using the estimates from Boeing for all weights (except engine) and performance for the vehicle, rotor and drive systems. Estimates for engine weights and performance were supplied by Rolls-Royce and scaled by Boeing as previously mentioned. Overall vehicle results were generated assuming COTS, EIS 2025, and EIS 2035 technology for both the engine and drive systems (while maintaining other vehicle systems technology levels fixed) to help isolate engine and drive system technology effects as previously mentioned.

COTS Engine and Drive System Technology Results

A summary of sizing results assuming COTS engine and drive system technology is given in Table 5. The minimum gross weights and fuel weights are very similar. For the mission requirements (speed, range, payload, etc.) rotor cruise tip speed of 500 fps resulted in the minimum gross weight and fuel weight cases; results were similar whether the speed reduction was achieved only from the engine or a multispeed gearbox. As shown in Figure 15, the further reduction in rotor cruise tip speed from 500 to 350 fps results in minimal improvement in rotor propulsive efficiency, while incurring penalties in engine SFC and gearbox and rotor weights evident from Table 5. This may point to a deficiency to capture the interaction between the rotor propulsive efficiency and vehicle aerodynamics (beyond contract scope for this effort) that was recently reported in Reference 8. At rotor cruise tips speeds of 650 fps, lower drive system weight (higher rpm yields lower torque and therefore lower weight per horsepower) does not overcome rotor propulsive efficiency (which shows up in fuel weight). Conversely at 350 fps rotor cruise tip speed, achieved through the engine alone, the significant loss in engine power and efficiency at the low 54 percent engine rpm shown earlier resulted in cruise power requirements determining the engine size. This increased the engine power requirement and weight, further penalized by poorer engine specific fuel consumption at cruise, resulting in the highest gross and fuel weights.

TABLE 5.—SUMMARY OF LCTR2 SIZING WITH COTS ENGINE AND DRIVE SYSTEM TECHNOLOGY

Rotor cruise tip speed	350	350	350	500	500	650
Engine cruise/Hover rpm	100%	77%	54%	100%	77%	100%
Drive system cruise/Hover rpm	54%	70%	100%	77%	100%	100%
Drive system type	2-speed	2-speed	1-speed	2-speed	1-speed	1-speed
Gross weight, lbm	108,325	^b 107,882	110,571	^b 106,132	^b 105,687	108,569
Fuel, lbm	^b 16,710	16,882	18,628	^b 16,624	^b 16,767	18,141
SHP	5186	5159	^a 5521	5168	5120	5278
Rotor weight, lbm	9529	9477	9641	9049	9011	9261
Drive system weight, lbm	9640	9131	8712	8296	7857	8138

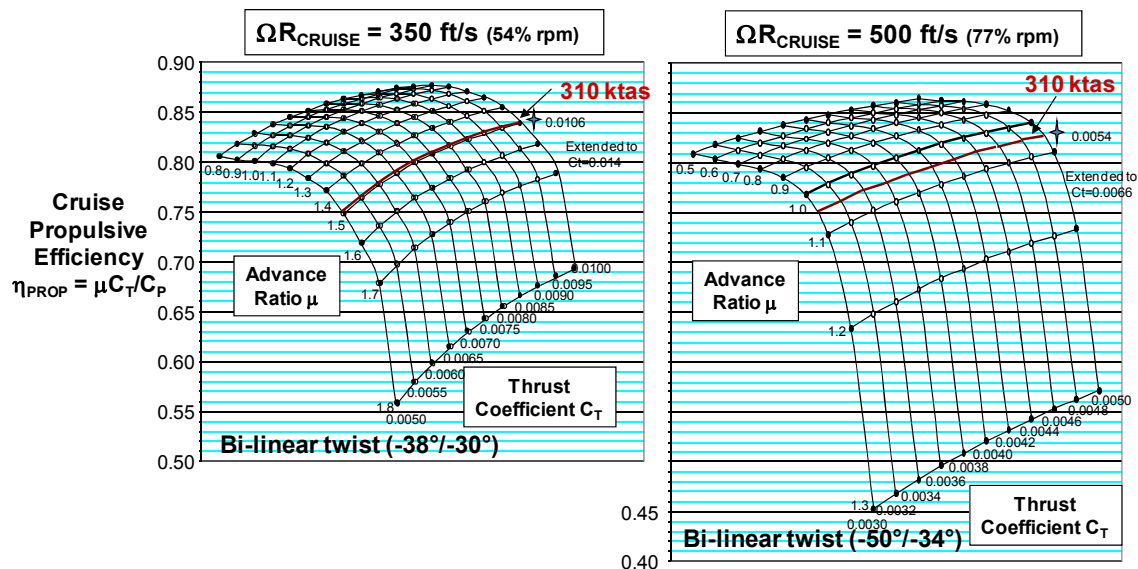
^aEngine sized by cruise requirement^bMinimum values for gross and fuel weight

Figure 15.—Rotor propulsive efficiency for 350 and 500 fps cruise tip speed designs.

2025 Engine and Drive System Technology Results

A summary of sizing results assuming EIS 2025 engine and drive system technology is given in Table 6. The minimum gross weights and fuel weights are again similar. The weight penalty for the wide-speed range power turbine generally resulted in heavier vehicles using more fuel than with COTS technology (the exception being the 350 fps rotor cruise tip speed, single-speed gearbox and engine at 54 percent cruise to hover rpm ratio). Results favor the single-speed gearbox at 350 and 500 fps rotor cruise tip speed. This makes sense for the assumptions made; the vehicle has already taken a weight penalty to achieve more efficient engine operation at reduced rpm (wide-speed range power turbine). Operation at 100 percent power turbine rpm at cruise while using a two-speed gearbox resulted in an additional penalty in engine fuel efficiency, which makes those cases even worse than for the COTS technology. As seen for the COTS results, reduced rotor cruise tip speeds also increased rotor and drive system weights (per shaft horsepower), although principally at 350 fps.

TABLE 6.—SUMMARY OF LCTR2 SIZING WITH 2025 ENGINE AND DRIVE SYSTEM TECHNOLOGY

Rotor cruise tip speed	350	350	350	500	500	650
Engine cruise/Hover rpm	100%	77%	54%	100%	77%	100%
Drive system cruise/Hover rpm	54%	70%	100%	77%	100%	100%
Drive system type	2-speed	2-speed	1-speed	2-speed	1-speed	1-speed
TOGW, lbm	115,017	^b 110,350	^b 108,567	113,105	^b 107,985	114,716
Fuel, lbm	19,459	^b 17,161	^b 16,647	19,363	^b 16,994	20,832
SHP	5462	5236	5132	5449	5179	^a 5564
Rotor weight, lbm	10023	9692	9548	9625	9188	9773
Drive system weight, lbm	9474	8776	8146	8336	7507	8108

^aEngine sized by cruise requirement^bMinimum values for gross and fuel weight

TABLE 7.—SUMMARY OF LCTR2 SIZING WITH 2035 ENGINE AND DRIVE SYSTEM TECHNOLOGY

Rotor cruise tip speed	350	350	350	500	500	650
Engine cruise/Hover rpm	100%	77%	54%	100%	77%	100%
Drive system cruise/Hover rpm	54%	70%	100%	77%	100%	100%
Drive system type	2-speed	2-speed	1-speed	2-speed	1-speed	1-speed
TOGW, lbm	97,540	^a 95,676	^a 95,014	95,734	^a 93,463	106,397
Fuel, lbm	13,452	^a 12,600	^a 12,633	13,404	^a 12,484	19,576
SHP	4664	4572	4523	4646	4516	5121
Rotor weight, lbm	8636	8502	8430	8163	7969	9061
Drive system weight, lbm	7538	7098	6619	6464	5915	6902

^aMinimum values for gross and fuel weight

2035 Engine and Drive System Technology Results

A summary of sizing results assuming EIS 2035 engine and drive system technology is given in Table 7. As before, the minimum gross weights and fuel weights are similar. The advanced 2035 engine and drive system technologies resulted in roughly 25 percent reduction in mission fuel and almost 12 percent reduction in vehicle gross weight from COTS technology. The case with 500 fps rotor cruise tip speed and single-speed gearbox had both the minimum gross and fuel weights. It is also important to note that the other 500 fps case (with the two-speed gearbox) just misses being one of the three best cases with respect to gross weight. For this case, the engine is not operating at its optimum cruise rpm for fuel efficiency and includes a weight penalty of 150 lb per unscaled engine for a wide-speed range power turbine that it is not using effectively. It is reasonable to assume that with a lighter power turbine designed for optimum performance at 100 percent rpm that it would be among the best in gross weight and possibly fuel weight as well. Reduced rotor cruise tip speeds also increased rotor and drive system weights (per shaft horsepower) for this technology level as well.

Conclusions

NASA contracted with The Boeing Company and Rolls-Royce to perform an investigation of different combinations of engine and gearbox variability to achieve a maximum of 50 percent rotor tip speed reduction from hover to cruise conditions. Advanced (EIS 2035) engine and drive system technology yielded an impressive 25 percent reduction in fuel weights and a 12 percent reduction in gross vehicle weight versus COTS technology. The 500 fps rotor cruise tip speed resulted in many of the minimum gross weights and fuel weights, although several of the 350 fps rotor cruise tip speed cases yielded similar results. For these minimum gross weights and fuel weights, results did not clearly favor the engine versus the two-speed gearbox approach to achieve the rotor cruise tip speed reduction. The reduction in rotor cruise tip speed from 500 to 350 fps resulted in increases in rotor and drive system weights that were not offset by improved rotor performance. A recent report (Ref. 8) has noted a favorable interaction between slowing the rotors and vehicle aerodynamics, but these analyses and effect were beyond the scope of this contract. Adding a wide-speed range power turbine to the engine, optimized for engine operation at 77 percent rpm, significantly improved the cases that depended on the engine alone to get the rotor cruise tip speed reduction to 54 percent. For other cases, the engine weight penalty (150 to 200 lb per unscaled engine) and minimal fuel efficiency improvement from a standard power turbine at 77 percent rpm (and a penalty at 100 percent engine rpm) significantly penalized those solutions. There are efforts underway to revisit the EIS 2035 cases using an engine with a “standard” power turbine. Once performed, results should give a clearer idea of the value of wide-speed range power turbine technology versus its weight and the multispeed gearbox approach for rotor cruise tip speed reduction. Finally, all these efforts are to be included in a comprehensive NASA contractor report, to help guide future project research efforts.

References

1. Johnson, W., Yamauchi, G.K., and Watts, M.E., “NASA Heavy Lift Rotorcraft Systems Investigation,” NASA/TP—2005-213467, September 2005.
2. Acree, C.W., Hyeonsoo, Y., and Sinsay, J.D., “Performance Optimization of the NASA Large Civil Tiltrotor,” International Powered Lift Conference, London, UK, July 22–24, 2008.
3. Wilkerson, Joseph B., and Smith, Dr. Roger L., “Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft,” The Boeing Company, NASA/CR—2009-214594, June 2009.
4. Schoen, A.H., Rosenstein, H., Stanzone, K.A., Wisniewski, J.S., “User’s Manual for VASCOMP II, The V/STOL Aircraft Sizing and Performance Computer Program” Prepared by the Boeing Vertol Company, D8-0375, 3rd revision, 1980.
5. Wilkerson, Joseph, “VASCOMP III, The V/STOL Aircraft Sizing and Performance Computer Program, User’s Manual,” Boeing Rotorcraft, D210-13635-1, 2002.
6. Liu, J., and McVeigh, M.A., “Design of Swept Blade Rotors for High-Speed Tiltrotor Application,” AIAA 91-3147, AIAA, AHS, and ASEE, Aircraft Design Systems and Operations Meeting, Baltimore, Maryland, September 1991.
7. Liu, J., Paisley, D.J., and Hirsh, J., “Tiltrotor Aerodynamic Blade Design by Numerical Optimization Method,” American Helicopter Society 46th Annual Forum, Washington, D.C., May 1990.
8. Acree, C.W., “Integration of Rotor Aerodynamic Optimization with the Conceptual Design of a Large Civil Tiltrotor,” AHS Aeromechanics Conference, San Francisco, CA, January 20–22, 2010.

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14. ABSTRACT In support of the Fundamental Aeronautics Program, Subsonic Rotary Wing Project, NASA is continuing to study the Large Civil Tiltrotor (LCTR) concept to help define/refine vehicle, system and subsystem attributes. These attributes can then be used to define performance requirements and identify new or advanced technologies to achieve an operational vehicle class. As part of this goal, NASA contracted with The Boeing Company and its subcontractor Rolls-Royce to perform an investigation of different combinations of engine and gearbox variability to achieve a maximum of 50 percent rotor tip speed reduction from hover to cruise conditions. Previous NASA studies identified the 50 percent rotor speed reduction minimized vehicle gross weight and fuel burn. The LCTR2 (LCTR-iteration 2) was the contracted study baseline for initial sizing. Rotor tip speed ratios (cruise to hover) of 100, 77, and 54 percent were analyzed for each combination of engine and gearbox speed reduction to achieve the chosen rotor tip speed ratio. Three different engine and gearbox technology levels were assumed; commercial off-the-shelf (COTS), entry-in-service (EIS) in 2025 and EIS in 2035. These technology levels were applied to determine each particular effect on vehicle gross weight and fuel burn, while other vehicle technologies were assumed constant. This report summarizes the work performed that is being put together into a comprehensive NASA contractor report. Some background on the LCTR concept and baseline vehicle will be given and then a discussion concerning the technical approach utilized. Major study assumptions and results will be presented and discussed. Finally conclusions will be drawn as well as suggestions provided for future efforts.					
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